

“Explosive regime” should dominate collisions of ultra-high energy cosmic rays

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Since the launch of LHC experiments it has been discovered that the high multiplicity trigger in pp, pA collisions finds events behaving differently from the typical (minimally biased) ones. In central pPb case it has been proven that those possess collective phenomena known as the radial, elliptic and triangular flows, similar to what is known in heavy ion (AA) collisions. In this paper we argue that at the ultra-high energies, $E_{\text{lab}} \sim 10^{20}$ eV, of the observed cosmic rays this regime changes from a small-probability fluctuation to a dominant one. We estimate velocity of the transverse collective expansion for the light-light and heavy-light collisions, and find it comparable to what is observed at LHC for the central $PbPb$ case. We argue that significant changes of spectra of various secondaries associated with this phenomenon should be important for the development of the cosmic ray cascades.

INTRODUCTION

Due to the air composition, passage of the ultra-high energy cosmic rays through atmosphere serves as a natural nuclear collision experiment. By “explosive” we mean a dynamical regime in which the system size becomes large comparing to the mean free path, resulting in collective flows, similar to the ones in accelerator experiments. “Ultra-high” collision energies refer to the highest ones observed in cosmic rays,

$$E_{\text{lab}} \lesssim E_{\text{max}} \sim 10^{20} \text{ eV}. \quad (1)$$

Detectors such as used by Pierre Auger Observatory (for recent updates see, e.g., [1]) observe events with the energy up to the so-called Greisen-Zatsepin-Kuzmin (GZK) bound [2]. For future comparison with the LHC observation it is convenient to convert the laboratory energy into the energy in the center of mass frame and use a standard Mandelstam invariant, assuming it is a pp collision,

$$\sqrt{s_{\text{max}}} = (2E_{\text{max}}m_p)^{1/2} \approx 450 \text{ TeV}. \quad (2)$$

While significantly higher than current LHC pp energy $\sqrt{s_{\text{LHC}}} = 8$ TeV, the jump to it from LHC is comparable to that from Tevatron $\sqrt{s} = 1$ TeV or RHIC $\sqrt{s_{\text{RHIC}}} = 0.5$ TeV. In view of smooth small-power s -dependence of many observables, the extrapolation to LHC worked relatively well, and further extrapolation may seem to be a rather straightforward task. And yet, smooth extrapolations using standard event generators plus, of course, the cascade codes do not reproduce correctly the experimental data of the Pierre Auger collaboration (e.g., the muon size [1]).

This calls for a new physics: let us mention one example. Farrar and Allen [3] proposed a “toy model” for the explanation of the data called “Chiral Symmetry Restoration” (CSR): their main idea is that somehow the pion production becomes suppressed. According to their simulations, a model in which mostly nucleons are produced explains the Pierre Auger data better.

We agree that for the high density of final particles per unit rapidity, dN/dy , expected at ultra-high collisions, corresponds to the quark-gluon plasma (QGP) production. QGP is indeed in a chirally restored phase with $T > T_c$. However, as we know from the heavy ion, pp and pA physics at LHC, this high density matter tends to explode. The process of particle production ends at a certain chemical freezeout temperature T_{ch} in a hadronic phase, close to the critical QCD temperature $|T_c - T_{ch}| \ll T_c$. The composition of secondaries remains remarkably energy- and system-independent, from few GeV to few TeV range of \sqrt{s} . There is no reason to think it will not be like that also in the case of cosmic rays.

Farrar and Allen argued that QGP explosion cannot be very important as it only produces elliptic flow, which is a relatively small effect – deformation of the angular distribution by few percents. While the statement itself is true, we disagree with the conclusion: the main effect of the explosion is not the elliptic deformation but the *radial* flow. It changes significantly the transverse momenta of the secondaries, especially nucleons, and therefore changes the production angles. Even though we do not perform any simulations of the secondary cascade in this paper and claim no explanation of ultra-high energy data, it is clear that the effects we discuss should change the visible size of the shower core, one of the key observables of the cosmic ray detectors. The modifications we discuss are based on a reasonably well understood physics, and thus should take place.

THE LHC FINDINGS

Searching for the quark-gluon plasma is the mainstream of the heavy ion physics. Starting from RHIC AA ($AuAu$) collisions it has been found that those are in a “macroscopic” or “explosive” regime. The spectra, two- and multi-particle correlations are well understood in the

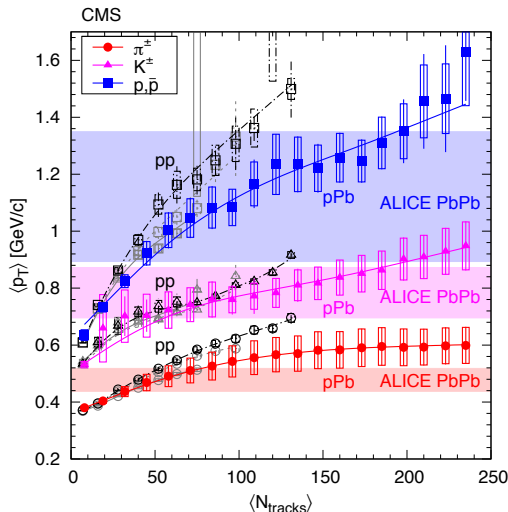


FIG. 1: (color online) (From [5].) Average transverse momentum of identified charged hadrons (pions, kaons, protons) in the range $|\eta| < 1$ as a function of the corrected track multiplicity in the rapidity acceptance $|\eta| < 2.4$, for pp collisions (open symbols) at several energies, and for pPb collisions (filled symbols) at $\sqrt{s_{NN}} = 5.02$ TeV. The shaded areas are the range of values for $PbPb$ collisions.

framework of relativistic hydrodynamics. Produced QGP has a nearly conformal equation of state ($\epsilon \sim T^4$, etc) and is strongly coupled, as is indicated by the small value of its viscosity. The same regime continues at the LHC domain, with even stronger collective flows.

Collisions involving proton beams – pp and pA – are different: their spectra do not show collective flows and are well reproduced by models based on the independent production and breaking of the QCD strings. However, from the start of the LHC experiments, the high multiplicity trigger of the CMS detector was able to select events, in which the so-called “ridge” phenomenon appeared [4]. It is an azimuthal correlation between secondaries which has a very long range in rapidity. Unfortunately, those events have a very small probability, $P_{\text{ridge}}^{pp} \sim 10^{-6}$, complicating so far their detailed studies.

Subsequent studies of pPb at LHC and dAu at RHIC have further revealed similar correlations which appear with probability $P_{\text{ridge}}^{pA} \sim \text{few \%}$, for “central” collisions. Those are studied and a number of observations shows that those correlations are indeed due to collective flows, similar to those seen in AA collisions [5]. Let us mention just two: (i) correlations involving 2, 4, 6 and even 8 particles indicate the same ellipticity v_2 ; (ii) the spectra of identified secondaries show clear signatures of the radial flow.

The simplest sign of the radial flow is that the mean transverse momentum grows with multiplicity quite substantially, and as shown in Fig. 1. The effect in pp

seems to be stronger than in central pA , which is in turn stronger than in central AA (the upper edge of the colored bands). Even better indicator of the radial flow is the so-called m_T slope of spectra of the identified secondaries, for discussion of those and comparison to hydrodynamics see Ref. [6].

THE “EXPLOSIVE REGIME” IN ULTRA-HIGH ENERGY COLLISIONS

Our main statement is that at the ultra-high energies $\sqrt{s_{\text{max}}}$ observed in cosmic rays, the “explosive regime” even in pA collision is expected to change from a very improbable $P \sim 10^{-6}$ fluctuation to the mean behavior, with $P = \mathcal{O}(1)$. The reason for it is simply an increase in mean particle (entropy) density with energy \sqrt{s} . The density is the number of particles per volume, and we will evaluate both subsequently.

The multiplicity (per unit rapidity – the length of the rapidity range is irrelevant as particles with very different rapidities do not interact) of pp collisions and AA collisions grow with energy in a bit different way, the fits including LHC data suggest

$$\frac{dN_{pp}}{dy} \sim s^{0.11}, \quad \frac{dN_{AA}}{dy} \sim s^{0.15}. \quad (3)$$

(The growth is initiated by pQCD and Pomeron effects, slowly increasing the number of color exchanges and the number of partons/strings involved. Lublinsky and one of us [7] have argued that the small extra growth in AA case comes from an extra entropy produced by the viscous effects during the hydro evolution.)

From the former extrapolation one gets the enhancement factor $(s_{\text{GZK}}/s_{\text{LHC}})^{0.11} \approx 2.5$, and from the latter the corresponding factor is ≈ 3.4 . Since the pA collision we expect to be somewhat in between these two regimes, we will use the following dN/dy enhancement factor,

$$\frac{dN^{\text{GZK}}/dy}{dN^{\text{LHC}}/dy} \approx 3, \quad (4)$$

from the LHC to the ultra-high energy edge for all types of collisions. From Fig. 1 alone one can thus expect certain growth of the mean p_T .

Unfortunately, it is not very clear what is the characteristic physical size of the system produced in high multiplicity pp collisions at the LHC: this issue is model-dependent and is intensively discussed at the moment.

(It can be deduced evolving hydrodynamics backwards in time – from an observed final state to the initial size. However, as we already mentioned, in the pp case no convincing evidences for collective flows were obtained so far due to a small probability/statistics.)

The problem of the initial system size becomes more clear for the collisions involving nuclei. In fact, primary

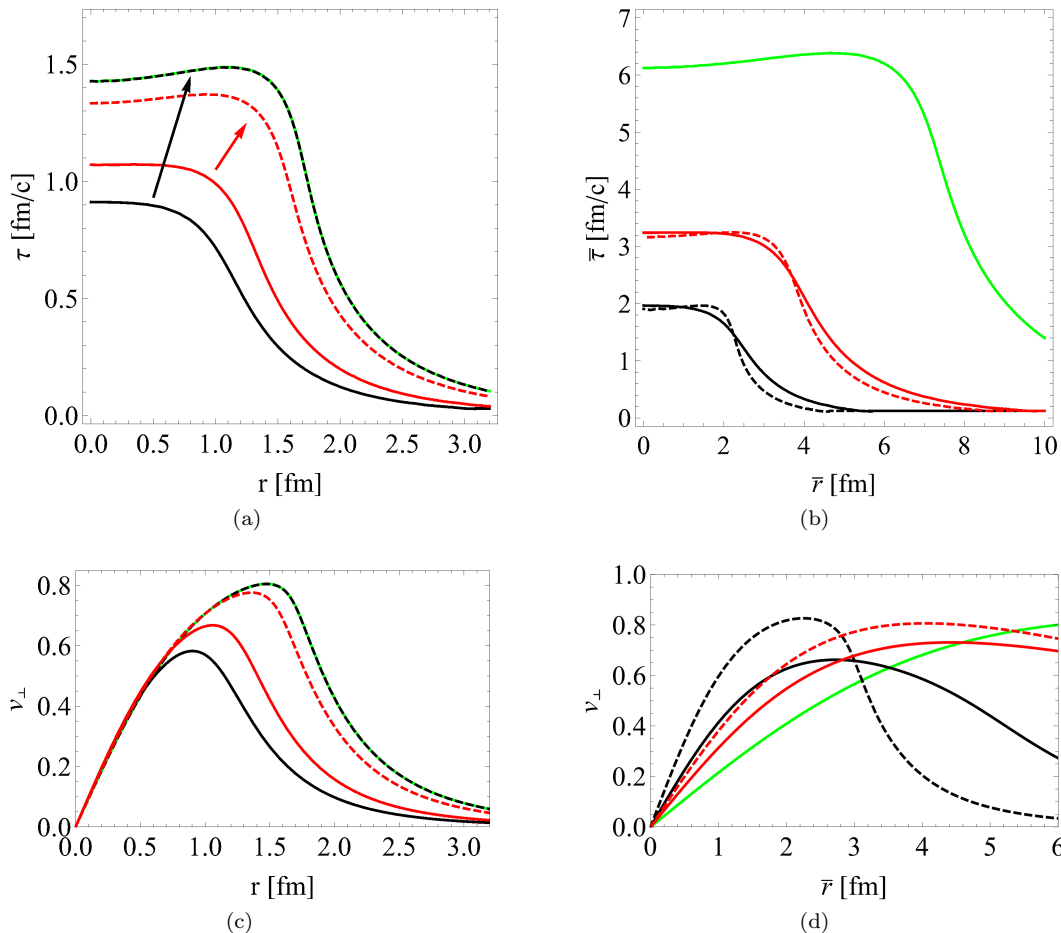


FIG. 2: (color online) (a) The freezeout surfaces in the (τ, r) plane and (c) the distribution of the transverse flow velocity on those surfaces. In both plots the green solid curve at the top is our “benchmark”, the central $PbPb$ collisions at LHC. Black solid line is for light-light collisions, black dashed (coincident with green by chance) are light-light collisions with the size compression. Similarly, red solid and red dashed are heavy-light collisions without and with the size compression, respectively. Two arrows connecting the pairs are to guide the eye. (b) The freezeout surfaces in the $(\bar{\tau}, \bar{r})$ plane (no rescaling) and (d) the distribution of the transverse flow velocity on those surfaces.

collisions and subsequent cascade of ultra high energy cosmic rays all happen in the Earth atmosphere, so the targets are not protons but light N or O nuclei. Furthermore, the projectiles themselves are also most likely to be nuclei: the distribution of primary collisions is incompatible with protons. It is either also some light nuclei or even a mixture including heavier ones, believed to be up to Fe [1].

Taking into account large pp cross section at ultra high energies, ~ 150 mb, one finds that its typical impact parameters $b \approx 2$ fm. Thus the range of the interaction in the transverse plane is comparable to the radius of the light nuclei (oxygen $R_O \approx 3$ fm) and therefore even in the pO collisions most of its 16 nucleons would become collision “participants”. For light-light AA collisions like OO the number of participants changes from 32 (central) to zero. Accidentally, the average number of participants is

comparable to the average number of participant nucleons $\langle N_p \rangle \approx 16$ in central pPb collisions at the LHC. So, in the light-light category we assume the initial transverse size to be R_O and multiplicity to 3 times that in central pPb collisions at the LHC. For heavy-light collisions (like FeO) it is likely that most nucleons participate, or $N_p^{FeO} \sim 70$. The size we assume to be $R_{Fe} \approx 4.8$ fm. The multiplicity scales as the number of participants, namely heavy-light is 70/16 of that in the light-light category.

Hydrodynamics provides a connection between the initial and the final properties of the system, and one should eventually find out the initial size, assuming the hydro works. For the problem at hand – to see how the result depends on the size of the system – it is convenient to follow the paper of Zahed and one of us [6], in which the radial flow is studied with the use of the (azimuthal angle and rapidity independent) Gubser’s solution [8]. From

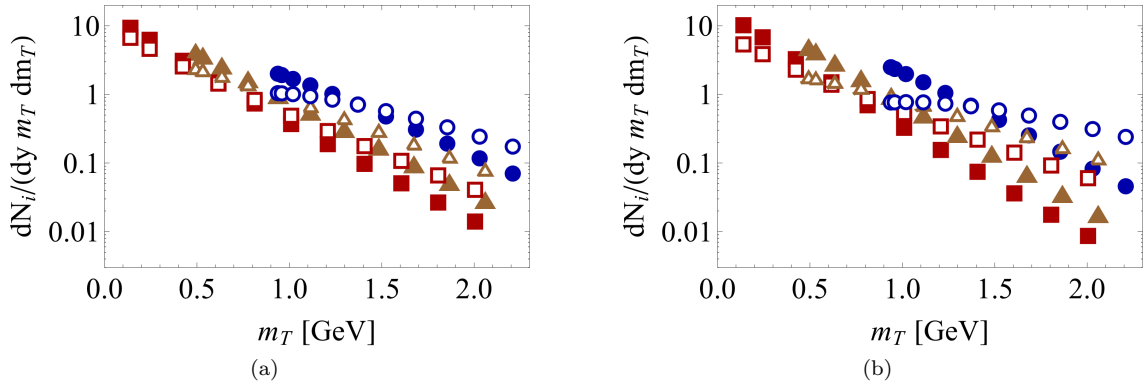


FIG. 3: (color online) Normalized spectra of pions (squares), kaons (triangles) and protons (discs) for the (a) heavy-light (e.g. FeO) and (b) light-light (e.g. pO) collisions. Open symbols correspond to the “compressed” cases, explained in the text.

particles	FeO	FeO comp.	pO	pO comp.	PbPb
π^\pm	0.56	0.69	0.53	0.76	0.73
K^\pm	0.71	0.88	0.66	0.96	0.92
p, \bar{p}	0.90	1.09	0.83	1.17	1.13

TABLE I: Mean p_T [GeV/c] for pions, kaons and protons obtained from the particle spectra. By “comp” we mean compressed initial state, as explained in the text.

the proper time and transverse radius $\bar{\tau}, \bar{r}$ (with the bar) we proceed to dimensionless variables $\tau = q\bar{\tau}$, $r = q\bar{r}$ by the scaling factor q , the first parameter of the model. The factor q is an inverse characteristic transverse size of the system at the beginning of the hydro phase (taken from e.g. the nuclei radii, pp total cross section, etc.). The solution for the transverse velocity and the energy density reads

$$v_\perp(\tau, r) = \frac{2\tau r}{1 + \tau^2 + r^2}, \quad (5)$$

$$\frac{\epsilon}{q^4} = \frac{\hat{\epsilon}_0 2^{8/3}}{\tau^{4/3} [1 + 2(\tau^2 + r^2) + (\tau^2 - r^2)^2]^{4/3}}. \quad (6)$$

The energy density has a second dimensionless parameter $\hat{\epsilon}_0$ related to the multiplicity dN/dy ,

$$\hat{\epsilon}_0 = f_*^{-1/3} \left(\frac{3}{16\pi} \frac{dS}{d\eta} \right)^{4/3}, \quad (7)$$

where $f_* = 11$ is the number of effective degrees of freedom in QGP and the entropy per (pseudo)rapidity, $dS/d\eta \approx 7.5 dN_{ch}/d\eta$, is proportional to the number of charged particles per unit rapidity [8]. Putting those to the same hydro solution we find the solid freezeout curves shown in Fig. 2. The left hand side of the plots shows them in rescaled coordinates: two coinciding curves correspond to the same flow, as the transverse velocity depends only on τ, r . The right hand side shows absolute coordi-

ates, in fm: in this case one can better compare the shapes of the surfaces for two initial size options we use.

We now remind that similar “naive” estimates would predict that the radial flow for pPb at the LHC is *weaker* than in central AA (the benchmark). As we already discussed in the Introduction, this contradicts the observations [5], and the solution proposed in [9] is the so-called “spaghetti collapse” (strings stretched between participating nuclei are attracted to each other and lead to a compression of the system). As a possibility, we would like to include this phenomenon as well. We do so in a very schematic way, by reducing the initial radius of the system by $\Delta R = -1$ fm. (The magnitude of the compression cannot be larger because at time exceeding 1 fm/c strings breaking occurs.)

The results are shown in Fig. 2 by the dashed lines. As one can see, the compression increases the flow. One can use the freezeout curves and substitute them to the Cooper-Frye formula [10] in order to obtain m_T particle spectra, where $m_T \equiv \sqrt{p_T^2 + m^2}$. As one can see from the Fig. 3, the compression affects the spectra, especially of the secondary protons. The m_T -scaling (exponential distributions with the same slope for all particles) is violated in the compressed case (open symbols) stronger, which is a clear evidence of the collective behavior. At the LHC such violation becomes significant only for rare high-multiplicity events [5], while here it becomes visible for average multiplicity. The mean p_T are also calculated from the spectra and presented in the Table I. The $\langle p_T \rangle$ is increased further if one takes into account the compression of the system – for the pO collision the effect is especially pronounced and leads to a strong enhancement.

SUMMARY AND DISCUSSION

We argue that the “explosive” regime, seen in *central* pA collisions at the LHC with few percent probability (and, of course, in AA) should become dominant (with probability $\mathcal{O}(1)$) in ultra-high energy pA collisions. It is even more clear for collisions of light-light (N, O) or heavy-light (FeO) nuclei.

We performed some estimates of the magnitude of the collective flow for those cases, and conclude that – within the uncertainties related to an equilibration mechanism at early stages – it is likely to be quite similar to those in the central $PbPb$ collisions at LHC.

Needless to say, we only did analytic estimates: predictions can obviously be made more accurate with more efforts. Furthermore, it would be needed to use the corresponding spectra as an input for the cosmic ray cascades, instead of the (extrapolated) pp spectra, to see how much the actual observables will be changed.

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